ARR No. 3G23

DEC 23 1946

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED
July 1943 as
Advance Restricted Report 3G23

KNOCKING TENDENCY OF AN AIR-COOLED AIRCRAFT-ENGINE CYLINDER WITH ONE AND WITH TWO SPARK PLUGS

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NACA

WASHINGTON

E-133

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ADVANCE RESTRICTED REPORT

KNOCKING TENDENCY OF AN AIR-COOLED AIRCRAFT-ENGINE CYLINDER WITH ONE AND WITH TWO SPARK PLUGS

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SUMMARY

Tests have been conducted with an air-cooled aircraft-engine cylinder to determine the effect on the knocking tendency of cutting out one spark plug when the engine is operating at or near the knock point with two spark plugs firing.

The results indicate that cutting out one spark plug will not lead to knock but, on the contrary, will actually stop or decrease knock that is occurring with both spark plugs firing. The power lost when one spark plug stops firing can be recovered by increasing the inlet pressure. In instances in which engine failure has occurred and it has subsequently been found that a spark plug had failed, it is possible that the primary failure was failure of the spark plug by overheating which caused pre-ignition.

INTRODUCTION

In the operation of an airplane, the pilot is interested in knowing what possible difficulties might be encountered through the accidental cutting out of one spark plug in one or more cylinders of the engine. The spark plug may fail during take-off or during flight. Such a failure will probably result in some loss of power because the effect of cutting out one spark plug has an over-all effect on the combustion process similar to that of retarding the spark. The reason for this fact is, that with two spark plugs mounted approximately diametrically opposite in the cylinder, the distance to be traversed by the flame front is approximately half the diameter of the engine chamber. When one spark plug ceases firing, the flame front from the remaining plug must traverse the entire combustion chamber. Naturally, this increased distance requires more time to complete the burning. If one spark plug is cut out, there may be some question as to whether or not this action will have any effect on detonation or preignition within the cylinder.

Results obtained with the NACA combustion apparatus (reference 1) and some unpublished engine data obtained at Langley Memorial Aeronautical Laboratory have indicated that the knocking tendency of the engine is decreased if one spark plug in a cylinder employing two spark plugs diametrically opposed ceases to fire. The present report presents additional data on this subject recorded from tests of a single-cylinder test engine made at LMAL.

Results similar to those presented in the present report have been obtained on an Allison V-1710-81 multicylinder engine in tests conducted at the Materiel Center, Army Air Forces.

APPARATUS AND TEST PROCEDURE

The engine used was a Wright 1820 G200 cylinder mounted on a Cooperative Universal Engine crankcase. The engine operating conditions were:

Compression ratio	7.0
Valve timing	
Inlet opens, degrees B.T.C.	15
Inlet closes, degrees A.B.C.	44
Exhaust opens, degrees B.B.C.	74
Exhaust closes, degrees A.T.C.	25
Valve lift (approx.), inch	5/8
Fuel injected into manifold,	
injection starts, degrees A.T.C.	70
Ignition timing, both plugs, degrees B.T.C.	20
Inlet-air temperature, °F	150
Oil-outlet temperature, °F	200
Engine speed, rpm	2000

Two BG-298-GS spark plugs were used, of which one had a chromel-alumel thermocouple in the tip of the center electrode. Reference fuel S-1 was used.

The ignition timing was selected by determining the spark advance for maximum power at a fuel-air ratio of 0.080 and then retarding the spark until the power dropped 1 percent. The spark timing varied about $\pm 0.5^{\circ}$ from cycle to cycle.

Knock was aurally determined by a microphone suspended above the engine. The output of the microphone was sent through an amplifier and a high-pass filter to headphones. The method was checked against an oscillograph and against the direct audible method and was found to be entirely reliable. Checks for the occurrence of preignition and afterfiring were made by momentarily cutting the ignition switch, but neither preignition nor afterfiring was encountered during the tests.

The procedure was as follows: The engine inlet pressure was raised until the engine was near the knock point. One spark plug was then cut out and the engine behavior was observed. Other tests were made with the engine knocking while it fired on both spark plugs; first one spark plug and then the other was cut out. Following these tests, a series of runs was made in which the engine was near the knock point while it operated on two spark plugs. One spark plug was then cut out and the engine was allowed to run for 55 minutes without a change in the amount of cooling air or in any other of the set conditions. The temperature of the rear spark-plug bushing was held at 400° F during the run with both spark plugs firing. After the front spark plug was cut out, all the other conditions were held constant and the temperatures were allowed to drift. Further tests were run in which curves of permissible inlet pressures against the fuel-air ratio were determined for operation with two spark plugs and with first one and then the other spark plug cut out. The rear spark-plug-bushing temperature was held at 400° F throughout these tests.

In the knock tests, the knock point was determined and the inlet pressure and the fuel flow were then dropped to 93 percent of the pressure and fuel flow that gave knock for two spark plugs. Thus, the inlet pressures given are 93 percent of the absolute pressure that caused audible knock at that condition.

A conventional spark-plug gasket thermocouple was installed under the rear spark plug for a few of the latest tests that were run with the engine. The temperature indicated by this thermocouple ranged from 5° F to 20° F lower than the temperature indicated by the thermocouple in the bushing. The difference is normally between 10° F and 15° F.

Supplementary tests have been made to determine the effect of spark-plug leakage upon electrode temperature. These tests were run on a Lycoming O-1230 cylinder with the use of a Bendix 41 G bottom-seating spark plug. This spark plug had grooves cut across the threads where the center screwed into the shell and a tube was arranged to carry the leakage to a point where it could be collected over water.

ANALYSIS

Rothrock and Biermann (reference 2) have shown that knock depends upon the interrelation of two factors, the end-gas temperature and the end-gas density. Factors that affect the end-gas density and temperature are the compression ratio, the inlet-air temperature, the inlet-air density, and the particular time during the engine cycle at which the peak cylinder pressure is reached. The number of spark plugs firing affects the time at which the peak pressure is reached.

The spark advance is known to have a very great effect on the knocking tendency. Peak pressure and temperature are usually reached shortly after the piston passes top center; an advance in the spark brings the point of maximum pressure nearer top center. Thus, the pressure and the temperature are higher than they were before the spark was advanced, and the knocking tendency is increased. Similarly, if the spark is retarded, the peak pressure and the peak temperature occur later in the cycle and are lower, and the knocking tendency is decreased. If an engine is operating on two spark plugs and one of the spark plugs ceases to fire, the mass rate of burning is decreased, the peak pressure occurs later in the cycle, and the knocking tendency should be decreased. The effect should be the same as if the spark were retarded.

The temperature trends of the cylinder head and barrel are also of interest. Because late spark timing has the same effect on the knocking tendency as a decrease in the compression ratio, in that the expansion ratio is lower, the exhaust gases will leave the cylinder at a higher temperature; and those portions of the engine around the exhaust port, and possibly the cylinder barrel, will be hotter when the burning is later completed. Some portions of the cylinder head, however, might run cooler with a retarded spark. Data obtained by Trimble and presented in reference 3 show that the temperature of a thermal plug in the cylinder head decreases as the compression ratio is decreased.

When one spark plug is cut out, its electrode temperature decreases because the combustion gases are always hottest near the ignition source (references 4, 5, and 6).

Recent unpublished tests of hot spark plugs in a CFR engine at LMAL have shown that, for mica-insulated spark plugs, the insulation fails at approximately the same temperature that causes preignition. It is therefore quite possible that cases of engine failure caused by preignition due to hot spark plugs have been attributed to failure of the insulation of the spark plug, a failure that would be noted when the engine was torn down for inspection.

It is emphasized that the experiments reported herein were conducted in order to determine the effect of cutting out one spark plug without a change in the ignition advance. No attempt was made to determine the effect on the knocking tendency of adjusting the spark advance for the single spark plug to the optimum setting.

Ricardo (reference 7) has reported tests with the E-35 engine, in which he varied both the number and location of the spark plugs and determined the highest useful compression ratio for each combination. In each case, Ricardo's tests were run with the spark timing set at the optimum for that particular number and location of spark plugs; that is, a greater spark advance was used with one spark plug than with two spark plugs. In general, he found that, when the spark timing was set at the optimum, the highest useful compression ratio with one spark plug firing was somewhat lower than was the case with two spark plugs firing.

RESULTS AND DISCUSSION

The results of the first test, in which one spark plug was cut out, are given in table I. The behavior of the engine temperatures is quite in accord with expectation as outlined in the analysis. The retarded combustion with only one spark plug firing lead to a lower expansion ratio and hotter exhaust gases. The exhaust-valve guide was therefore hotter. The head temperatures decreased, showing the same trend as Trimble's data (reference 3), in which a decrease in compression ratio led to a decrease in the thermal-plug temperatures. The barrel temperature remained constant.

The engine was then brought up to the knock point and first one spark plug and then the other was cut out. The results are given in table II. Although the engine was knocking with both spark plugs firing, the knock stopped when either spark plug was cut out. The temperature data were taken about 5 minutes after the spark plug was cut out. All of the temperatures dropped except the exhaust-valve-guide temperature and the temperature of the rear of the middle of the barrel, which showed a temperature rise of 2° F with only the front spark plug firing.

A more complete series of tests was then made in which the engine was brought to the knock point at a fuel-air ratio of 0.082, the inlet pressure and fuel flow were dropped 7 percent, the front spark plug was cut out, and the temperatures were allowed to drift for 55 minutes with the engine running. Figures 1 to 4 show the results of this series of tests. All of the head temperatures (fig. 1) dropped except that of the exhaust-valve guide. All of the barrel temperatures (fig. 2) dropped except those of the front of the barrel. At the end of 10 minutes the piston temperature (fig. 3), taken at the exhaust end zone, that is, under the exhaust valve, had dropped about 30° F; and it remained constant for the rest of the run. All flange temperatures (fig. 3) dropped. Before this series of tests was made, the spark-plug-electrode thermocouple had become shorted at a point somewhat above the tip of the electrode, and the values recorded are about half those normally encountered. The trend, however, is the same as is encountered when the thermocouple is reading properly. Invariably, the instant the spark plug is cut out, the electrode temperature drops very markedly (fig. 3). This effect is in accord with the analysis. The indicated thermal efficiency (fig. 3) decreased when one spark plug was cut out and continued to fall throughout the run. The indicated fuel consumption (fig. 4) increased slightly when the spark plug was cut out and kept on increasing as the indicated mean effective pressure dropped and kept on dropping.

Another series of tests was made to determine whether the power lost when one spark plug was cut out could be recovered without knock by increasing the inlet pressure. Runs were made at various fuel-air ratios ranging from full rich to very lean at 93 percent of the inlet pressure that caused knock with two spark plugs firing.

The maximum permissible inlet pressure, the maximum permissible indicated mean effective pressure (except at the rich and lean ends of the curve), and the maximum permissible air weights per cycle (fig. 5) were all higher with one spark plug than with two. The probable reason for the lower indicated mean effective pressure at rich and lean mixtures is the greater difficulty in getting good ignition with only one spark plug. The indicated specific fuel consumption was higher with the one spark plug. It is interesting to note from figure 5, that, when the engine was operating at an indicated mean effective pressure of 180 pounds per square inch, a lower fuel consumption (0.435, point B) was permissible with only the rear spark plug firing than with both spark plugs firing (0.480, point A). This statement is in accord with the fact that, if the compression ratio of the engine is such that a rich mixture is required to suppress knock, a lower minimum permissible fuel-air ratio and a lower specific fuel consumption can be had by decreasing the compression ratio or retarding the spark.

Figure 6 shows that the temperature of the electrode in the front spark plug decreased about 100° F when the spark plug was cut out. The temperatures were again too low as mentioned previously. Piston temperature with only the rear spark plug firing (fig. 7) was approximately 30° F lower than with both spark plugs firing, and flange temperatures were from 2° F to 6° F lower when only the rear spark plug was firing. With the exception of the temperatures of the exhaust-valve guide and of the positions near the exhaust valve, the general trend of the cylinder-head temperatures was lower when only the rear spark plug was firing (fig. 8).

Indicated thermal efficiencies (fig. 9) were lower when the engine was operating on only the rear spark plug. Although the trend of the barrel temperatures was not very definite, it may be seen that only slight differences exist between the two conditions investigated. The barrel temperatures just under the head are shown in figure 10 with the temperature of the rear spark plug plotted for comparison. The temperature of the rear spark-plug bushing was held as near 400° F as possible by varying the cooling-air velocity. The temperatures with one spark plug firing are in general slightly higher than with both spark plugs firing.

Runs similar to those illustrated in figures 5 to 10 were made with the front spark plug firing instead of the rear spark plug. The results with two spark plugs firing and the results with only the front spark plug firing are compared in figures 11 to 16 and show trends similar to those shown in figures 5 to 10.

Care should be exercised in the interpretation of the temperature data given in figures 5 to 16. Inasmuch as the rear spark-plug bushing was held at 400° F during the tests (except at some points at rich mixtures, for which the cooling-air pressure of some of the tests could not be reduced sufficiently to maintain the temperature of the rear spark-plug bushing), the trends shown by the temperatures of the other points in the cylinder represent only the manner in which these temperatures change with respect to the rear spark-plug-bushing temperature as engine conditions are changed. Thus, the fact that the barrel and head temperatures shown for operation with the front spark plug only (figs. 13, 15, and 16) are higher than those for operation either with both spark plugs or with only the rear spark plug is readily explained as follows: It is known that the gas temperatures in the combustion chamber of an engine are highest in the part of the chamber nearest the spark plug (reference 5). In an engine operating on two spark plugs, therefore, when one spark plug is cut out, the temperature of the entire region around that spark plug will drop. This result is shown also by the fall in temperature of the spark-plug electrode. In the case in which the rear spark plug is cut out, the temperature of the spark-plug bushing dropped. The reference point for controlling the engine temperatures is the rear spark-plug bushing; the cooling-air pressure drop was therefore reduced to bring the bushing temperature back to 400° F, and the temperatures of the other parts of the engine rose to higher values than were encountered with two-spark-plug operation. The true criterion of the temperature trends when one spark plug is cut out is found in tables I and II; in figures 1 to 3, for which the cooling-air pressure drop was not changed; and in figure 17, which shows the cooling-air pressure drop across the engine cowling necessary to maintain the temperature of the rear spark-plug bushing at 400° F for the four series of runs shown in figures 5 and 11.

It is believed that engine failures, attributed to knock, which have been accompanied by spark-plug failure, should be attributed to spark-plug failure through overheating and consequent preignition, rather than to failure because the spark plug ceased firing. Preignition itself may cause knock, but it should be emphasized that the primary failure is then preignition and not knock.

A spark plug may become overheated if a gas leak occurs in the spark plug. In order to determine this effect, some tests have been run with a Lycoming O-1230 cylinder with an artificially induced leak around the center electrode of one spark plug. A thermocouple was installed in the tip of the center electrode. The results of these tests are summarized in table III. The data of table III show that leakage near the center electrode of the spark plug raises its temperature decidely when the leakage rate is of the order shown. Leakage of 1 cubic centimeter per minute was assumed to be negligible. According to the data listed, the leakage rate of 65 cubic centimeters per minute caused an increase in center-electrode temperature roughly comparable with the increase caused by an increase of about 10 inches of mercury in inlet-air pressure. The permissible rate of leakage for new mica spark plugs is 1/2 cubic centimeter per minute at a pressure of 150 pounds per square inch.

CONCLUSIONS

The data presented herein indicate that for the spark timing as used in present aircraft engines in which the spark advance is generally set for slightly less than best power:

1. The cutting out of one spark plug will not lead to engine knock or preignition but, on the contrary, will actually stop or decrease knock that is occurring with both spark plugs firing.

2. If one spark plug stops firing, the power thus lost can be recovered, without danger from knock, by increasing the inlet pressure. Some loss of thermal efficiency and, hence, some increase of specific fuel consumption is encountered by this procedure.

3. In instances in which engine failure has occurred and it has subsequently been found that a spark plug had failed, it is possible that the primary failure was failure of the spark plug by overheating which caused preignition.

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TABLE I

COMPARISON OF ENGINE DATA WITH BOTH SPARK PLUGS FIRING

AND WITH FRONT SPARK PLUG FIRING

[Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20° B.T.C.; inlet pressure, 93 percent of pressure causing knock for two spark plugs; inlet-air temperature, 150° F]

Intake pressure (in. Hg abs.)	imep (lb/sq in.)	Spark plugs firing	Fuel-air ratio	Knock	Temperature, °F			
					Center of head between valves	Exhaust-valve guide	Rear spark-plug bushing	Rear of middle of barrel
36.2	192.2	Both	0.083	No	411	574	403	286
	185.6	Front		No	396	593	373	286

TABLE II

COMPARISON OF ENGINE DATA WITH BOTH SPARK PLUGS FIRING

AND WITH FIRST FRONT AND THEN REAR SPARK PLUGS FIRING

[Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20° B.T.C.; inlet pressure, pressure causing knock for two spark plugs; inlet-air temperature, 150° F]

Spark plugs firing	Fuel-air ratio	Knock	Temperature, °F			
			Center of head between valves	Exhaust-valve guide	Rear spark-plug bushing	Rear of middle of barrel
Both	0.080	Yes	411	582	400	289
Front		No	398	590	374	291
Rear		No	404	584	389	285

TABLE III

EFFECT OF LEAKAGE ON SPARK-PLUG TEMPERATURE

[Lycoming O-1230 cylinder]

Intake pressure (in. Hg abs.)	Leakage (cc/min)	Electrode temperature (°F)	Temperature increase, °F	
			Due to inlet pressure	Due to leakage
34	0	717	----	----
38	[a]1	756	39	----
42	[a]1	799	82	----
46	[a]1	824	107	----
34	34	787	----	70
38	44	834	----	78
42	56	887	----	88
46	65	920	----	96

[a]Approximate

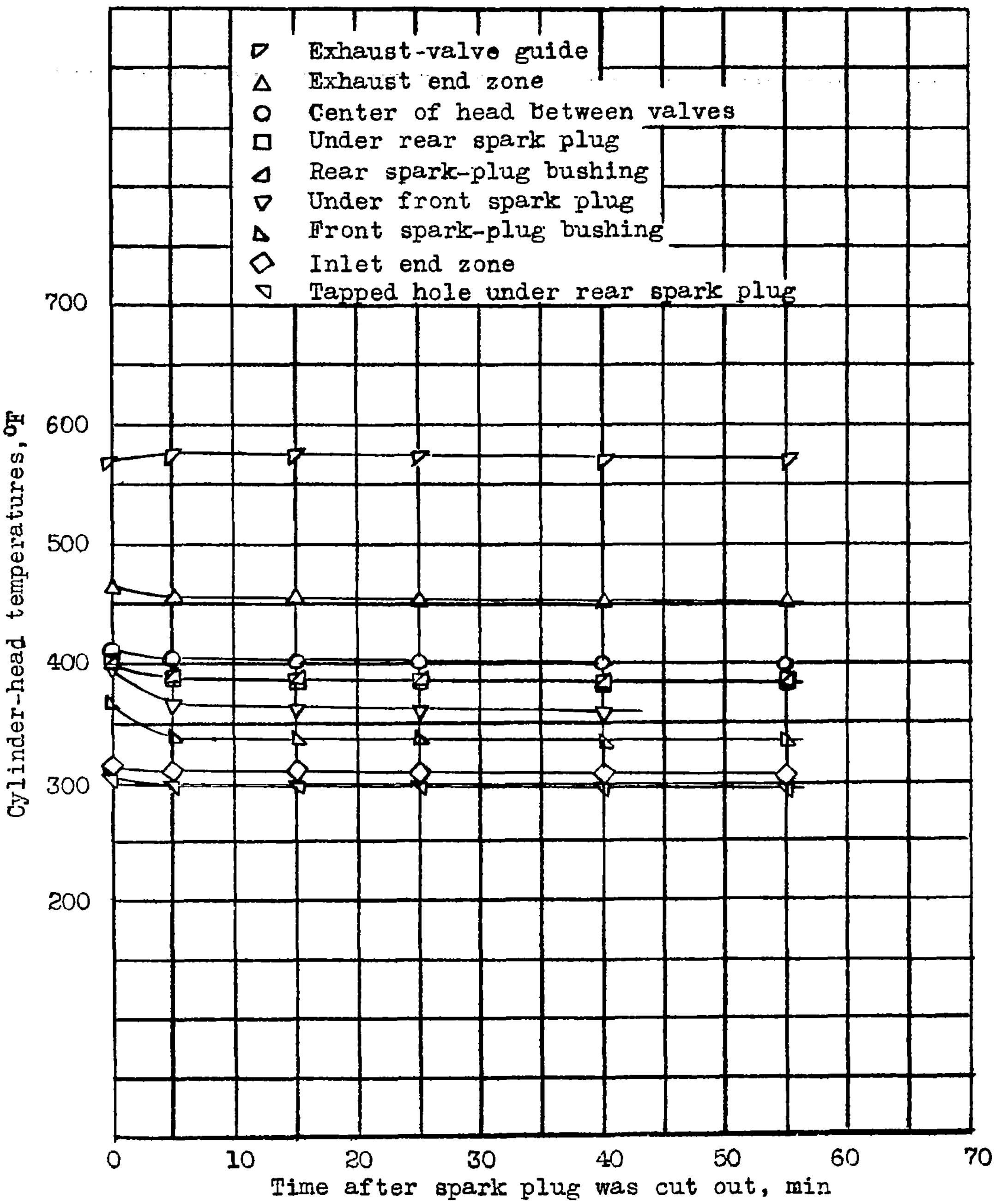

Figure 1.- Trend of cylinder-head temperatures after front spark plug was cut out. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of pressure causing knock for two spark plugs; inlet-air temperature, 150°F.

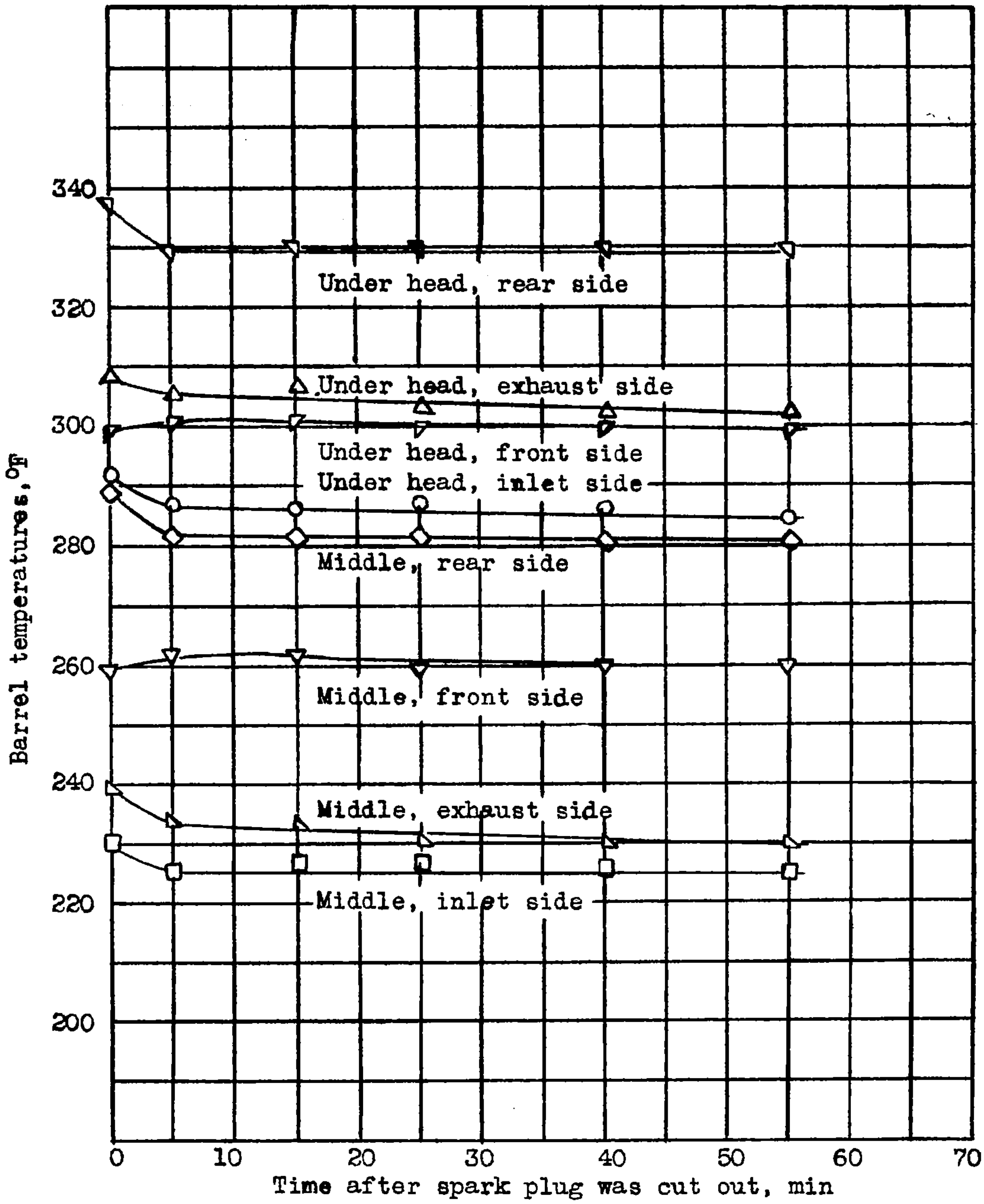

Figure 2.- Trend of barrel temperatures after front spark plug was cut out. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of pressure causing knock for two spark plugs; inlet-air temperature, 150°F.

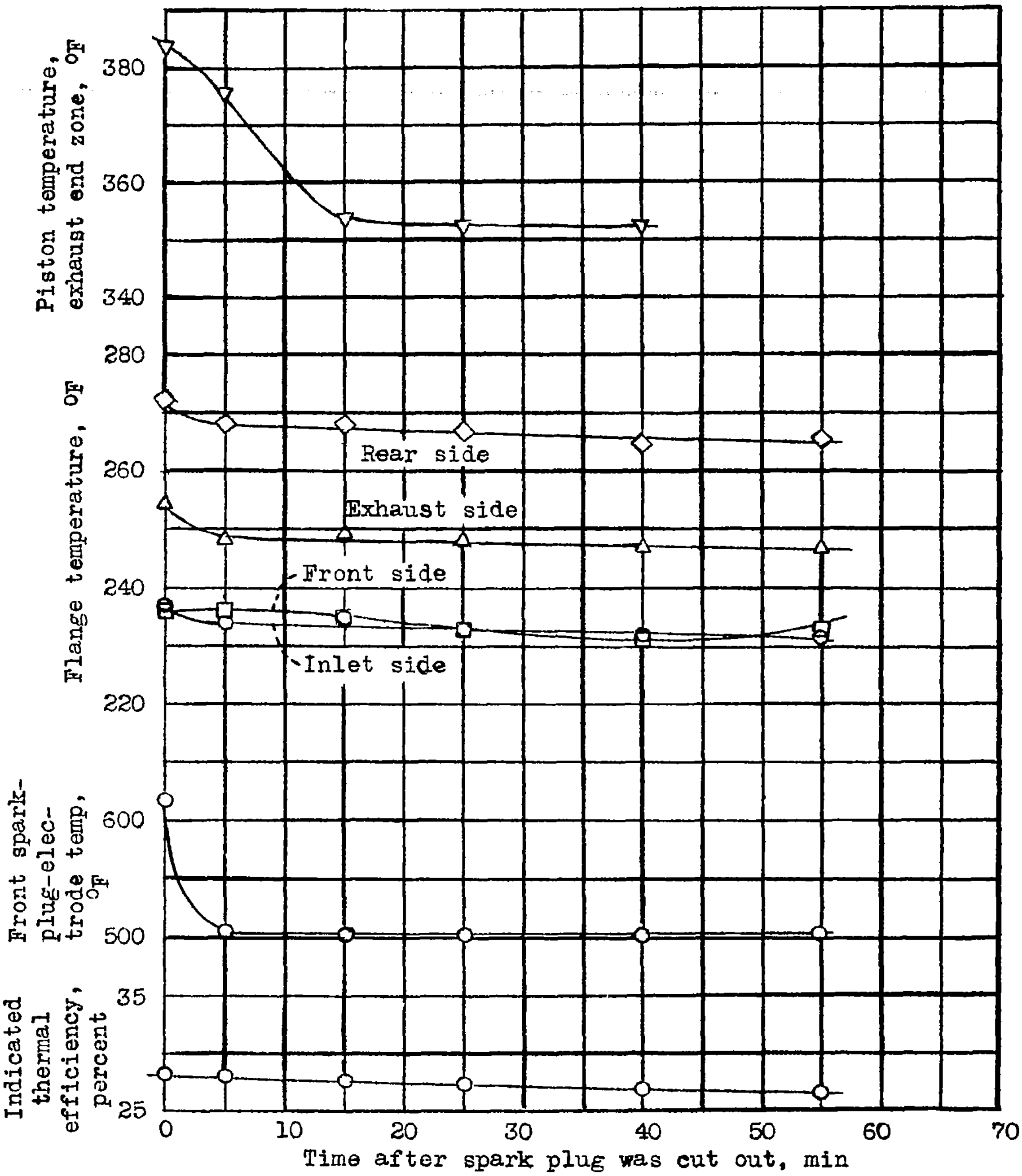

Figure 3.- Trend of piston temperature, flange temperatures, front spark-plug-electrode temperature, and indicated thermal efficiency after front spark plug was cut out. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of pressure causing knock for two spark plugs; inlet-air temperature, 150°F.

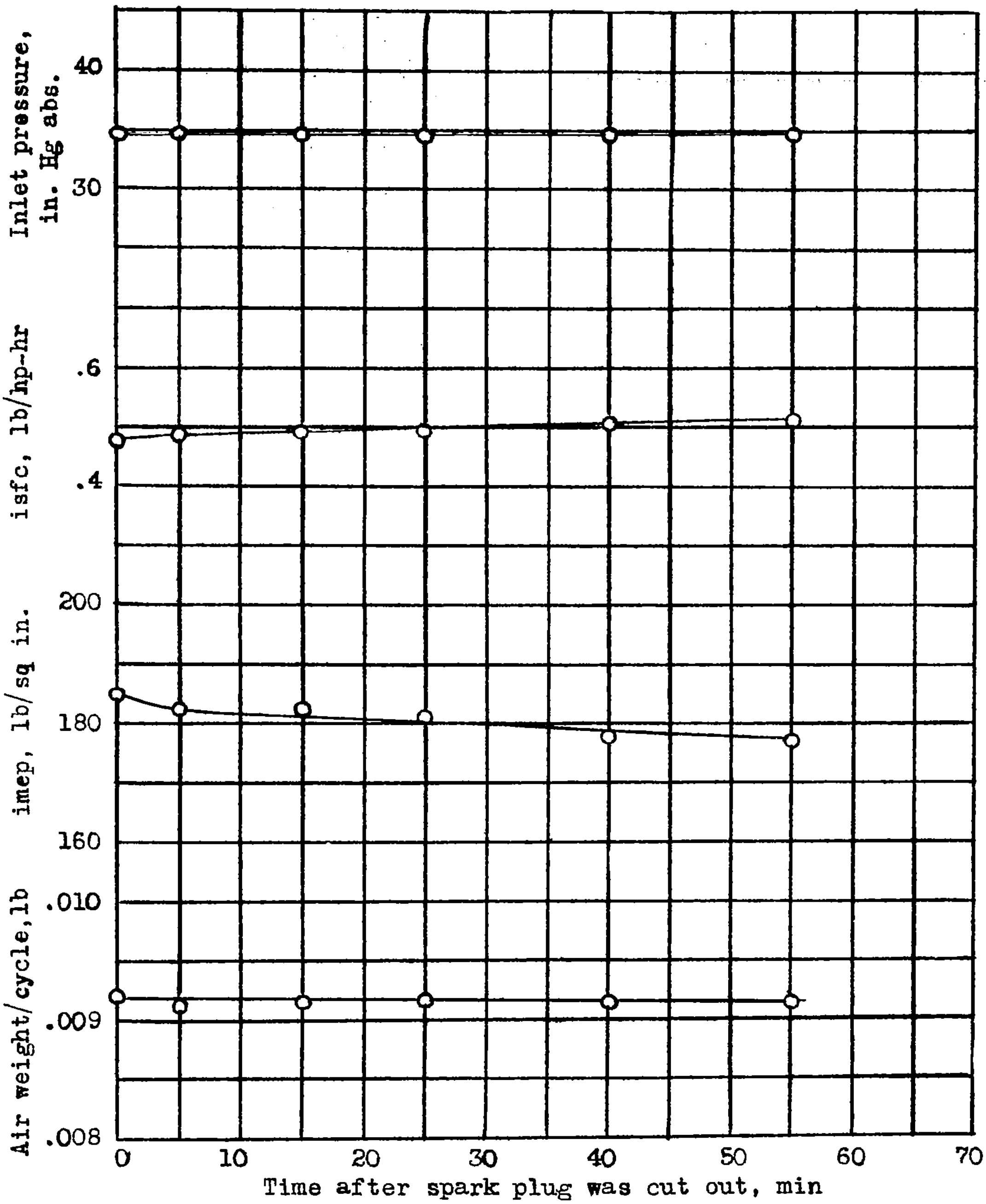

Figure 4.- Inlet pressures, indicated specific fuel consumption, indicated mean effective pressure, and air weight per cycle after front spark plug was cut out. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of pressure causing knock for two spark plugs; inlet-air temperature, 150°F.

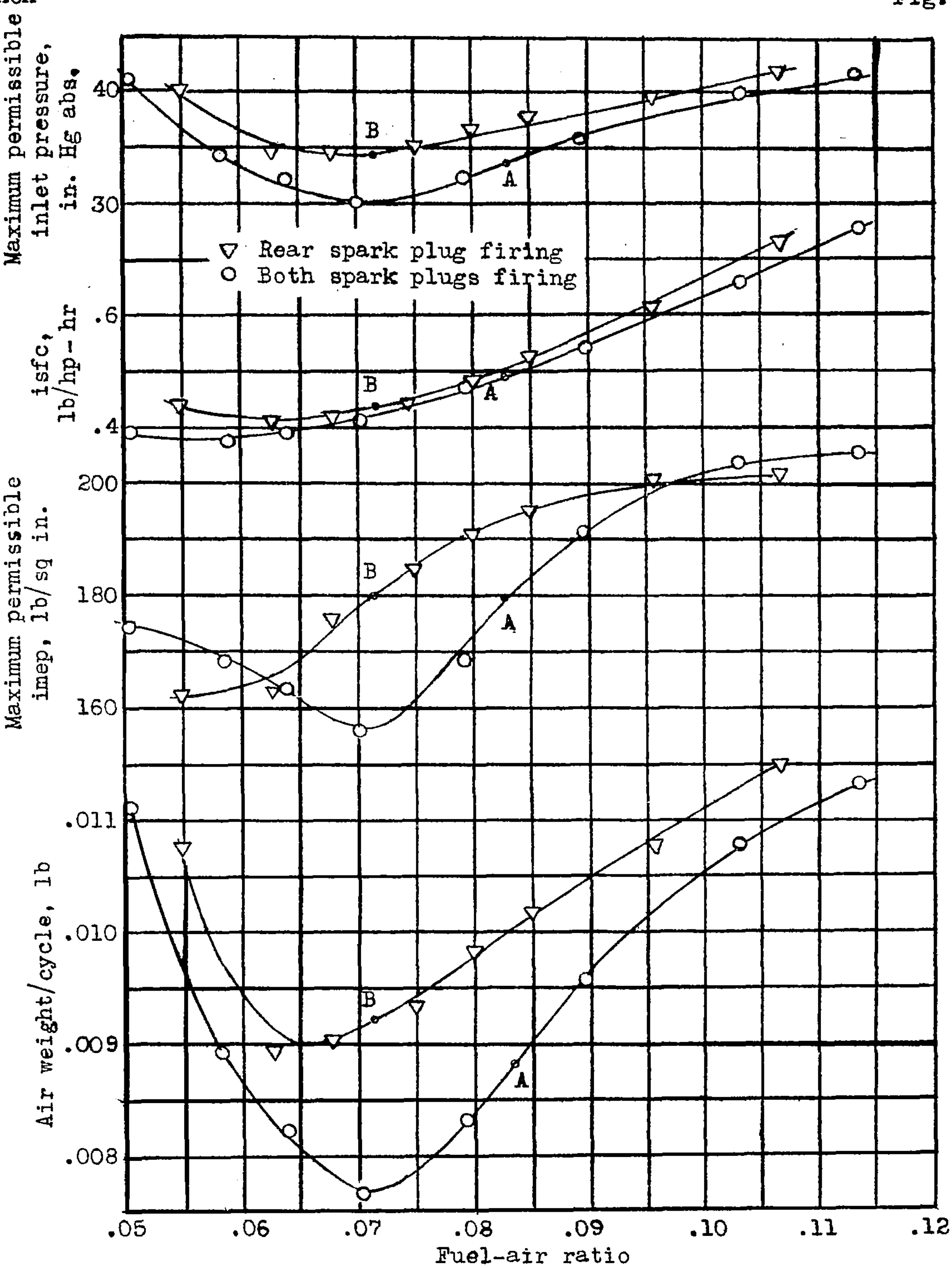

Figure 5.- Comparison of permissible inlet pressure, indicated specific fuel consumption, maximum permissible indicated mean effective pressure, and air weight per cycle with rear spark plug firing and with both spark plugs firing. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of knock; inlet-air temperature, 150°F; temperature of rear spark-plug bushing, 400°F.

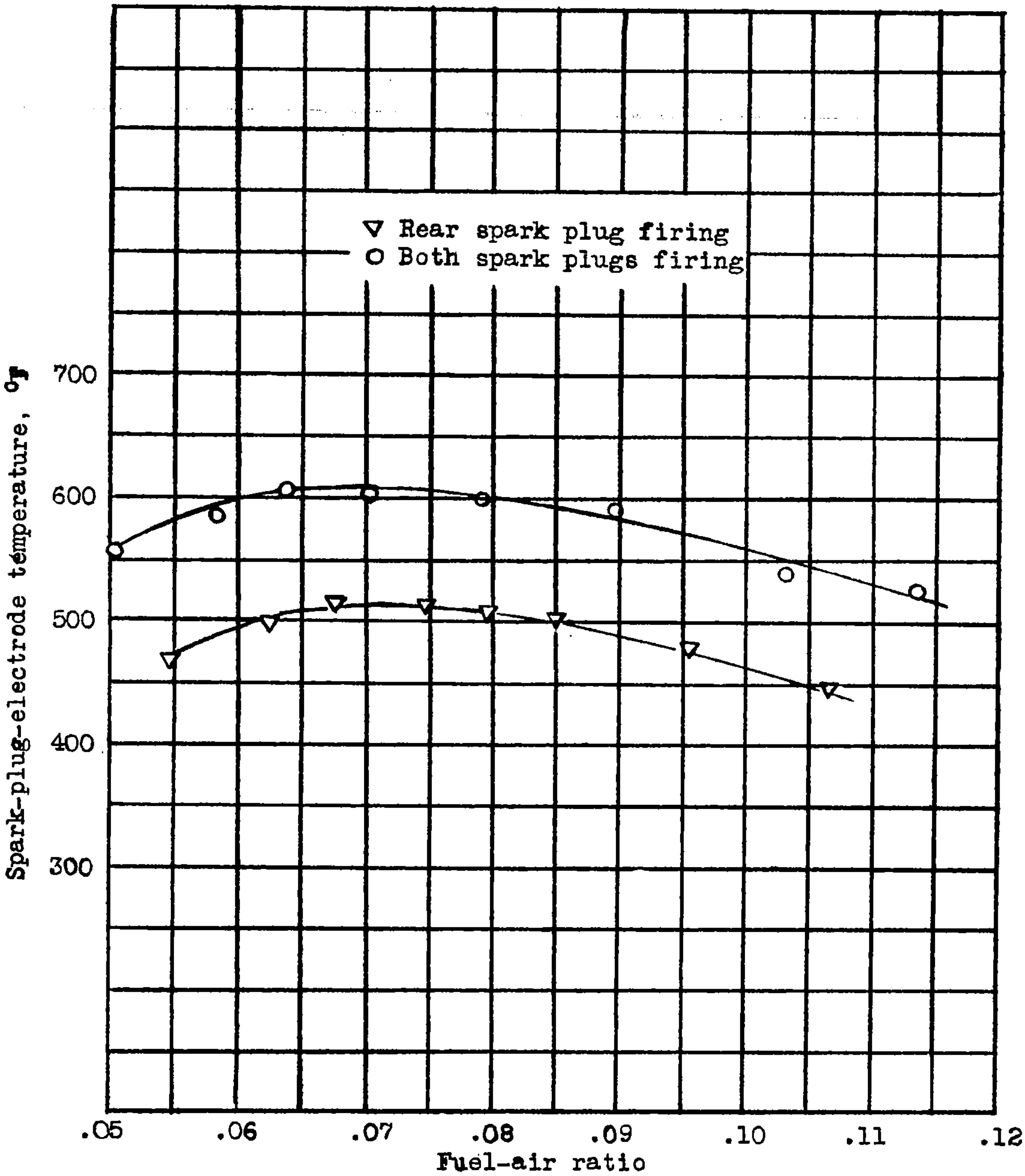

Figure 6.- Comparison of temperature trend of front spark-plug electrode with rear spark plug firing and with both spark plugs firing. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of knock; inlet-air temperature, 150°F; temperature of rear spark-plug bushing, 400°F.

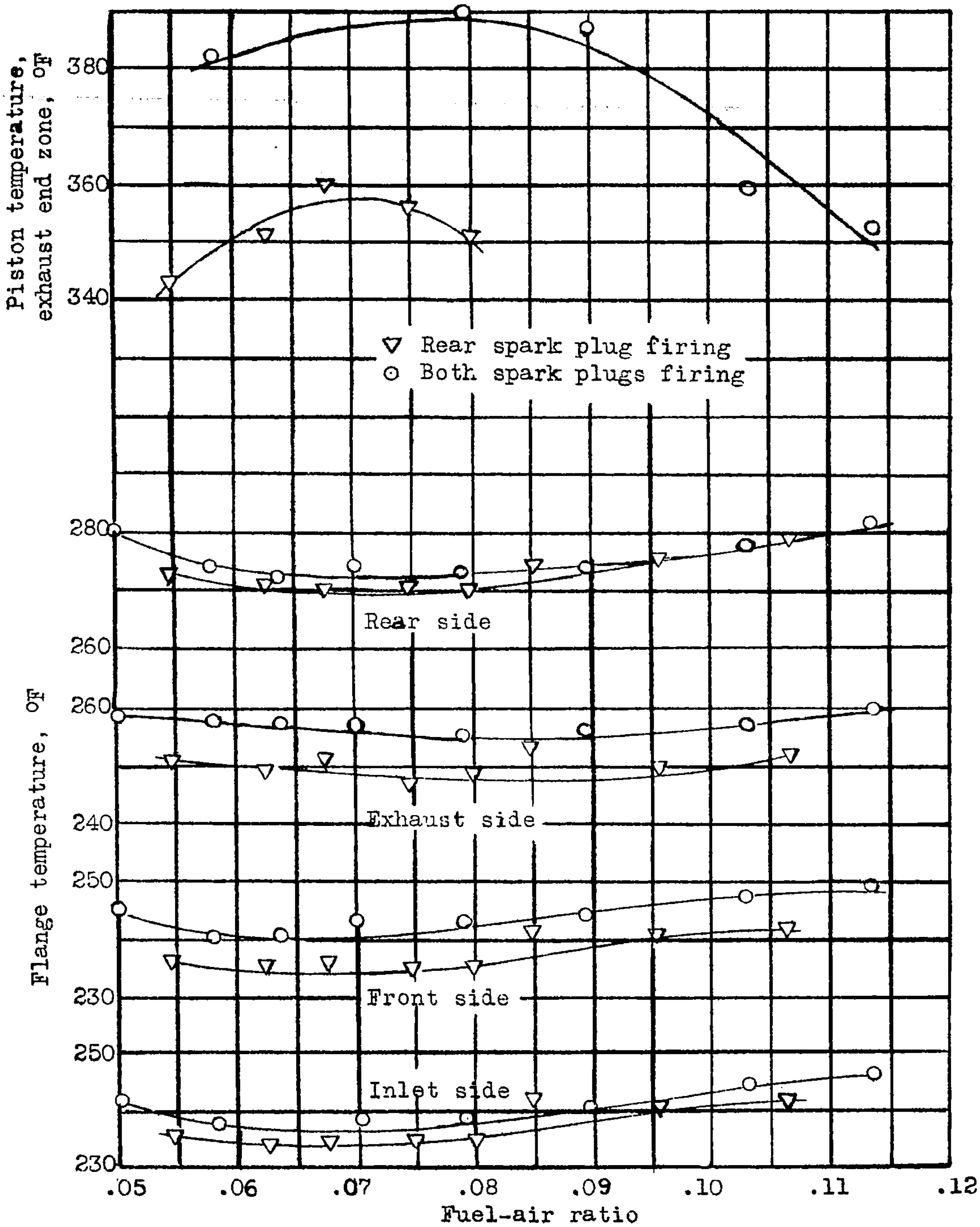

Figure 7.- Comparison of piston and flange temperatures with rear spark plug firing and with both spark plugs firing. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of knock; inlet-air temperature, 150°F; temperature of rear spark-plug bushing, 400°F.

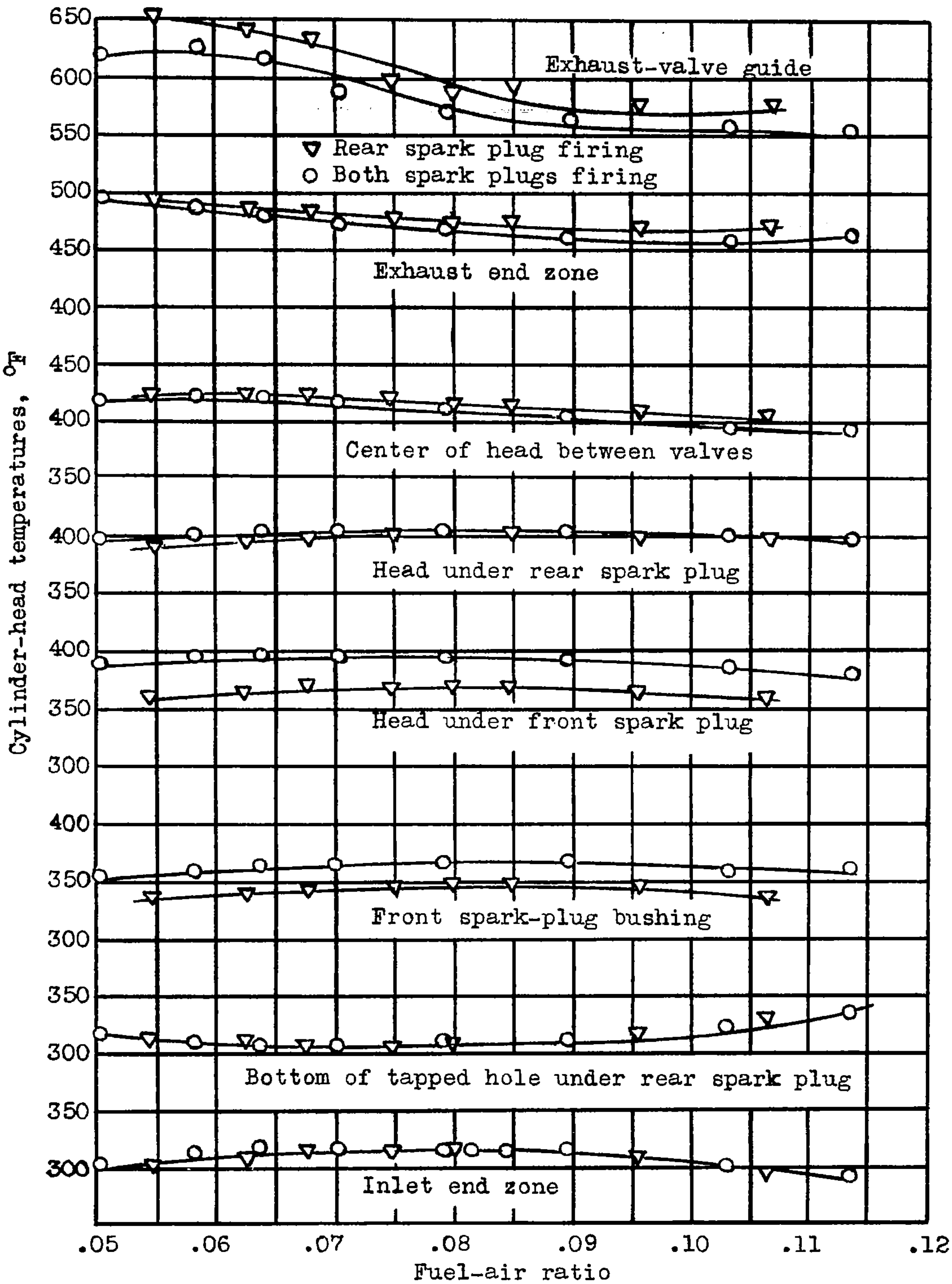

Figure 8.- Comparison of cylinder-head temperatures with rear spark plug firing and with both spark plugs firing. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of knock; inlet-air temperature, 150°F; temperature of rear spark-plug bushing, 400°F.

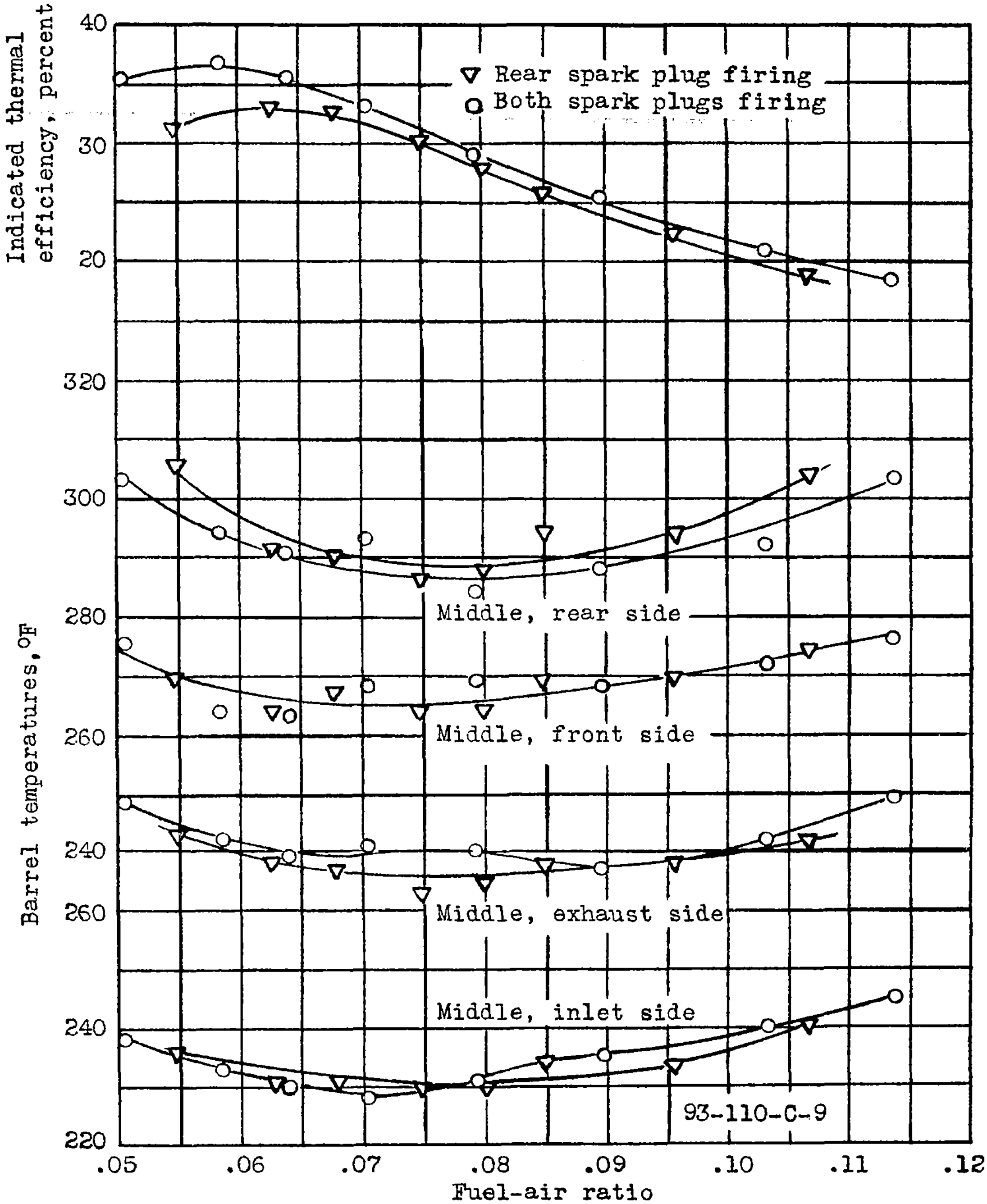

Figure 9.- Comparison of indicated thermal efficiencies and barrel temperatures with rear spark plug firing and with both spark plugs firing. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of knock; inlet-air temperature, 150°F; temperature of rear spark-plug bushing, 400°F.

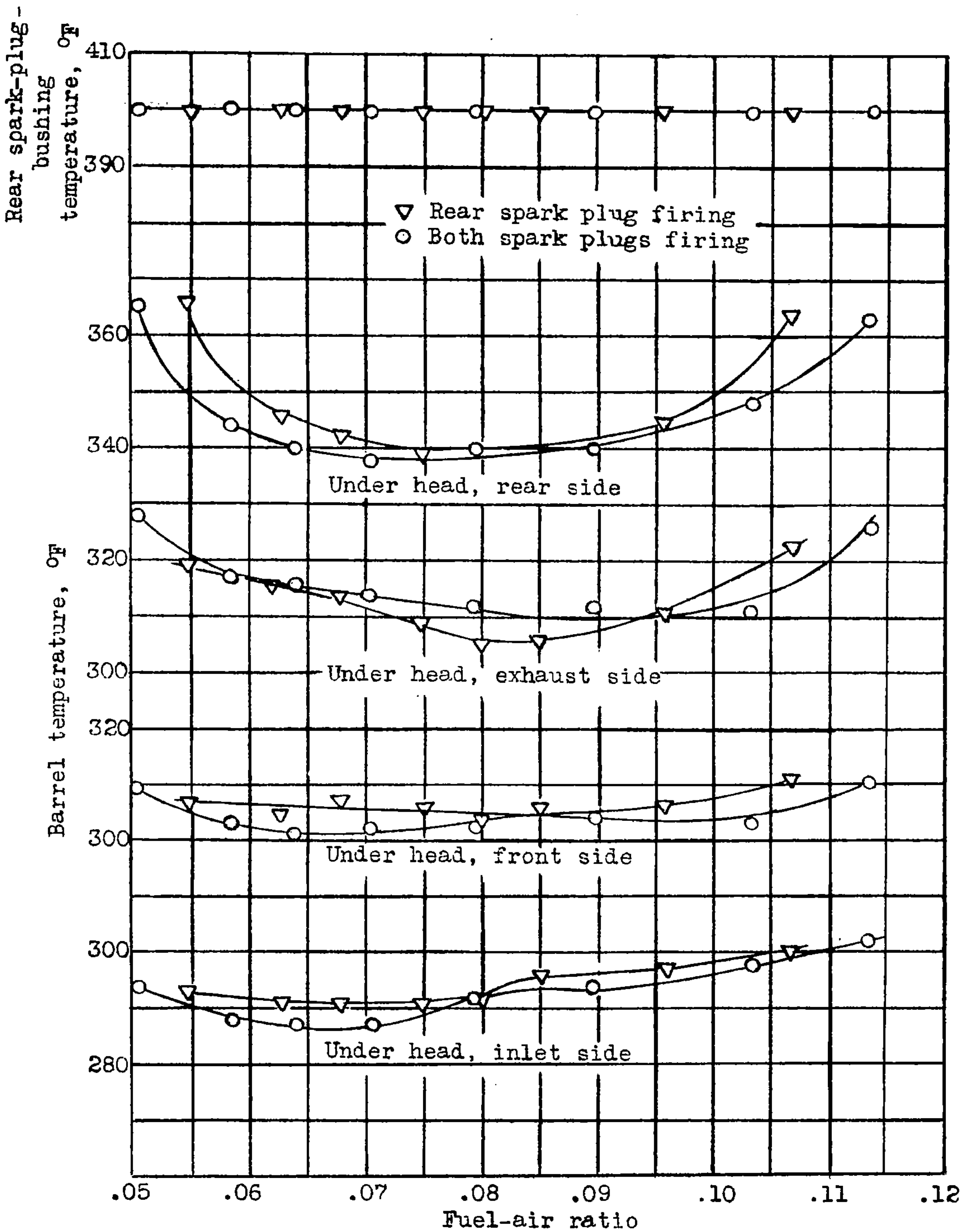

Figure 10.- Comparison of barrel temperatures with rear spark plug firing and with both spark plugs firing. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of knock; inlet-air temperature, 150°F; temperature of rear spark-plug bushing, 400°F.

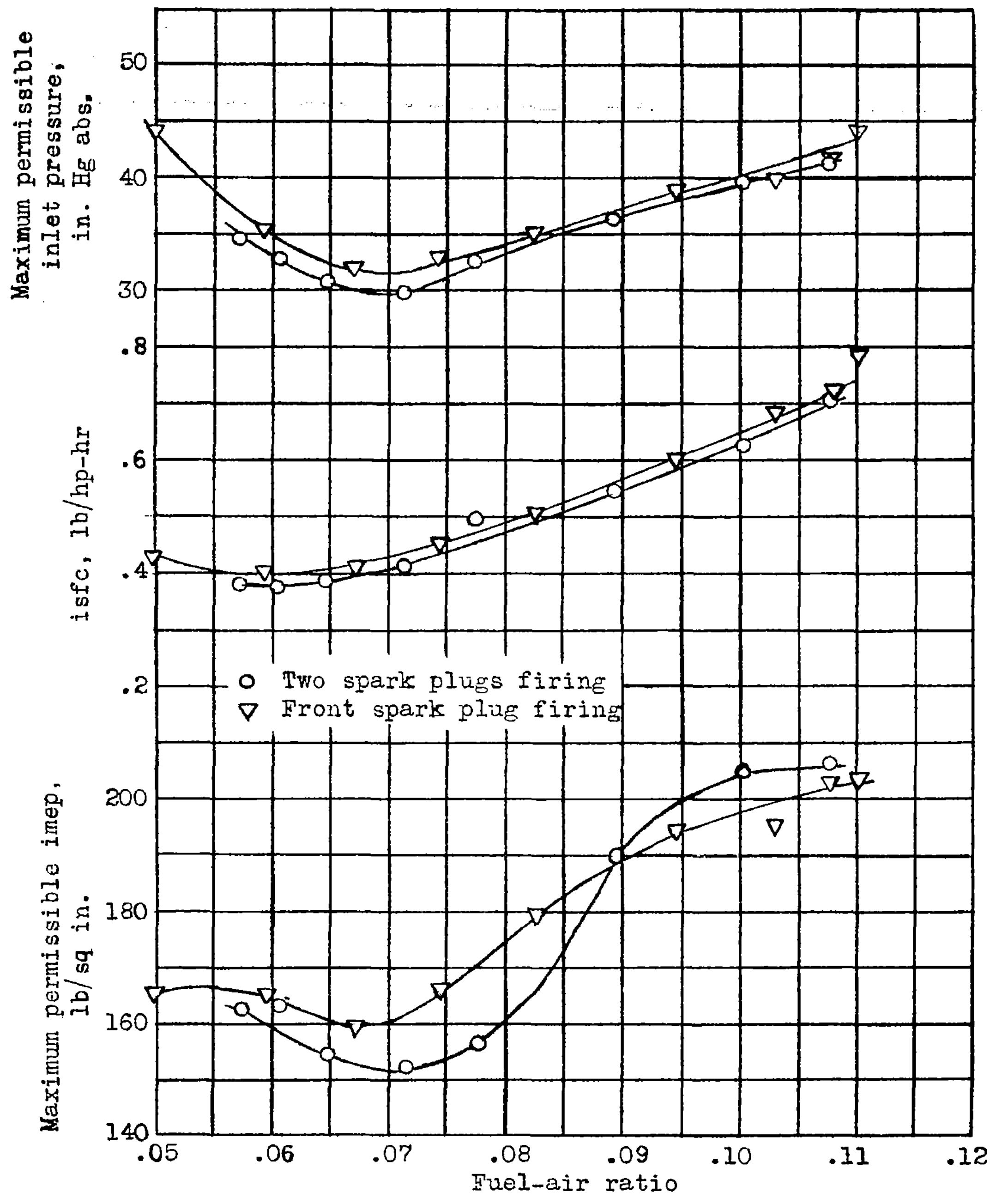

Figure 11.- Comparison of maximum permissible inlet pressure, indicated specific fuel consumption, and maximum permissible indicated mean effective pressure with front spark plug firing and with both spark plugs firing. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of knock; inlet-air temperature, 150°F; temperature of rear spark-plug bushing, 400°F.

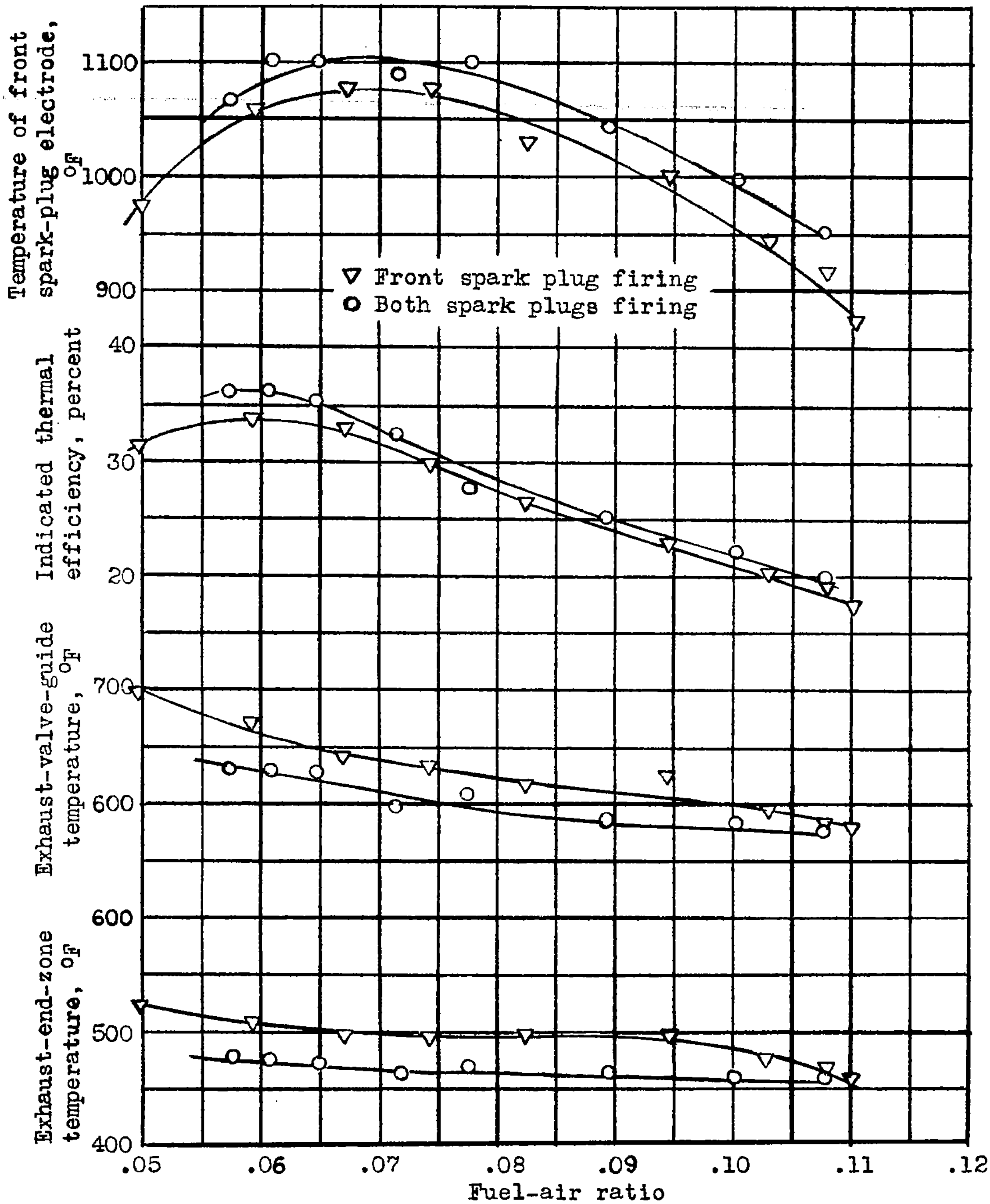

Figure 12.- Comparison of spark-plug-electrode temperatures, indicated thermal efficiencies, and temperatures of two places in cylinder head, with front spark plug firing and with both spark plugs firing. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of knock; inlet-air temperature, 150°F; temperature of rear spark-plug bushing, 400°F.

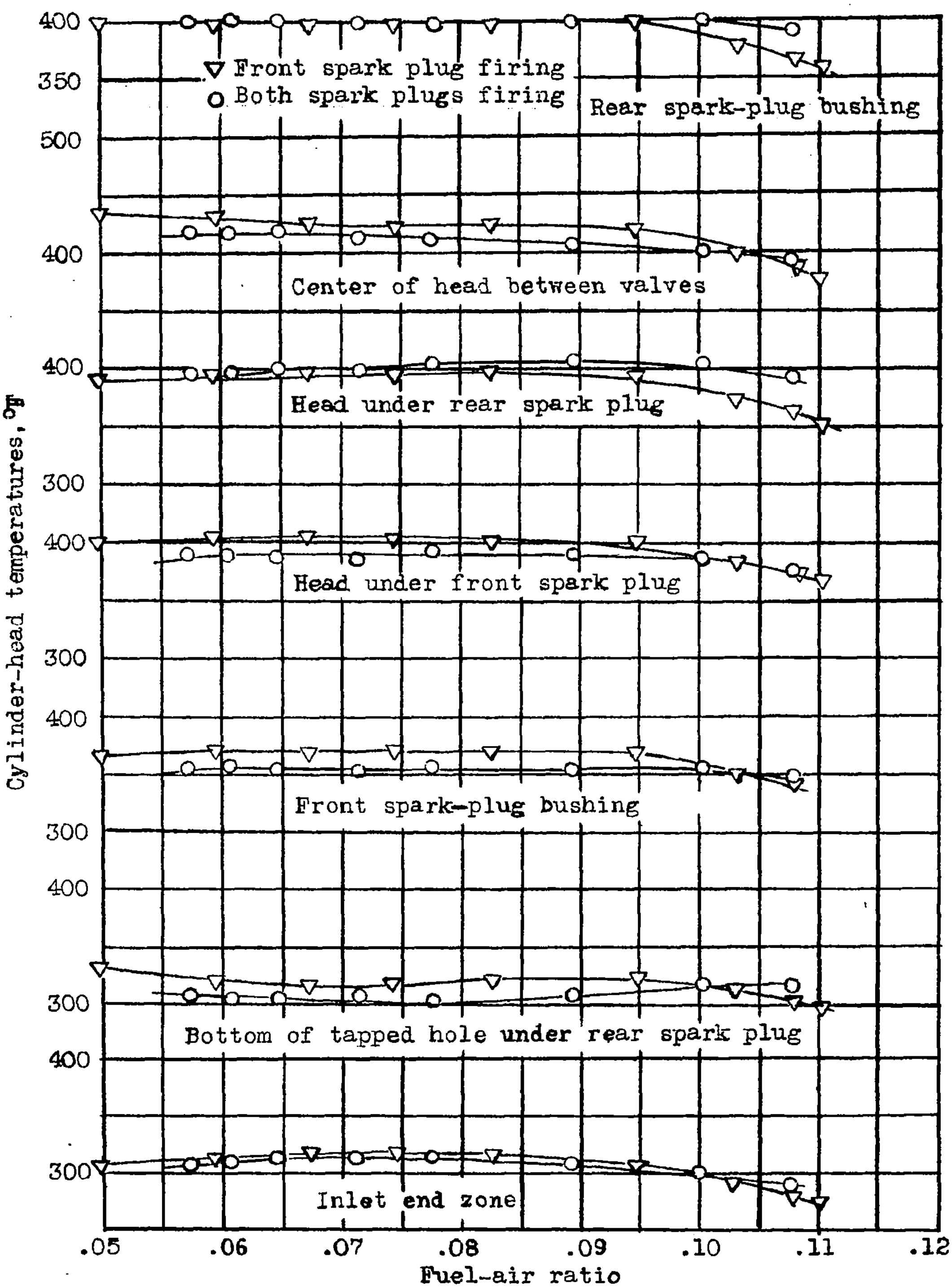

Figure 13.- Comparison of cylinder-head temperatures with front spark plug firing and with both spark plugs firing. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of knock; inlet-air temperature, 150°F; temperature of rear spark-plug bushing, 400°F.

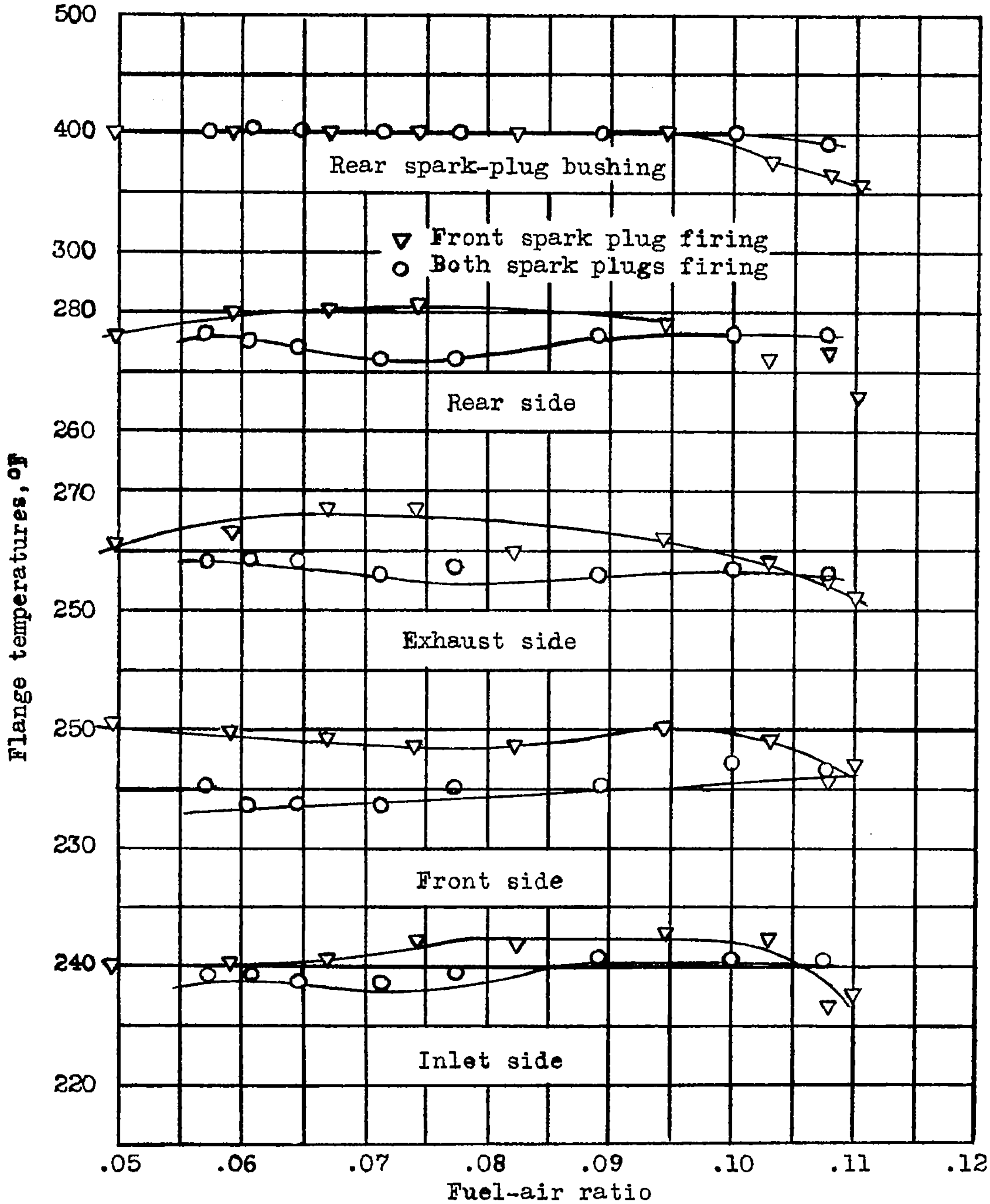

Figure 14.- Comparison of flange temperatures with front spark plug firing and with both spark plugs firing. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of knock; inlet-air temperature, 150°F; temperature of rear spark-plug bushing, 400°F.

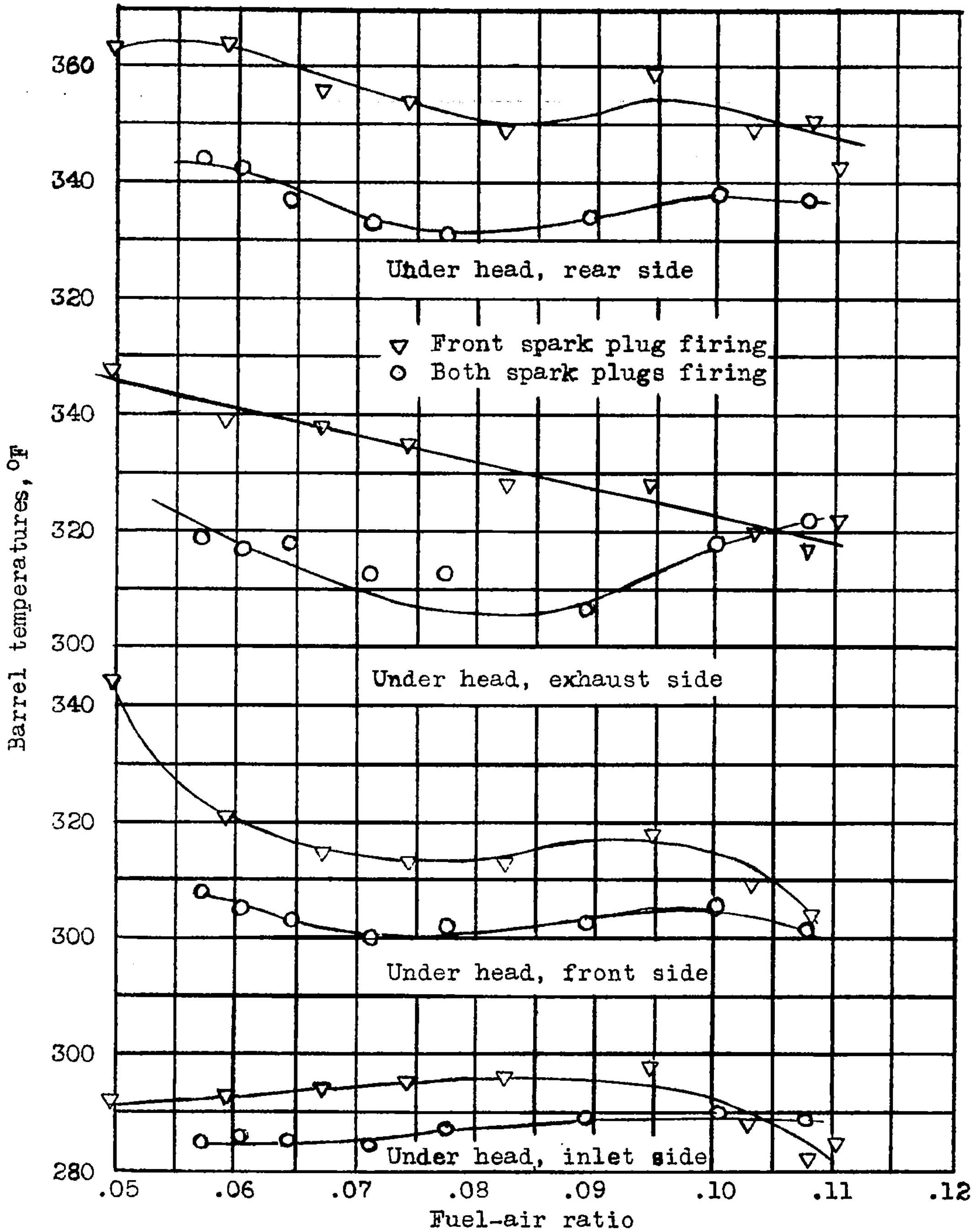

Figure 15.- Comparison of barrel temperatures with front spark plug firing and with both spark plugs firing. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of knock; inlet-air temperature, 150°F; temperature of rear spark-plug bushing, 400°F.

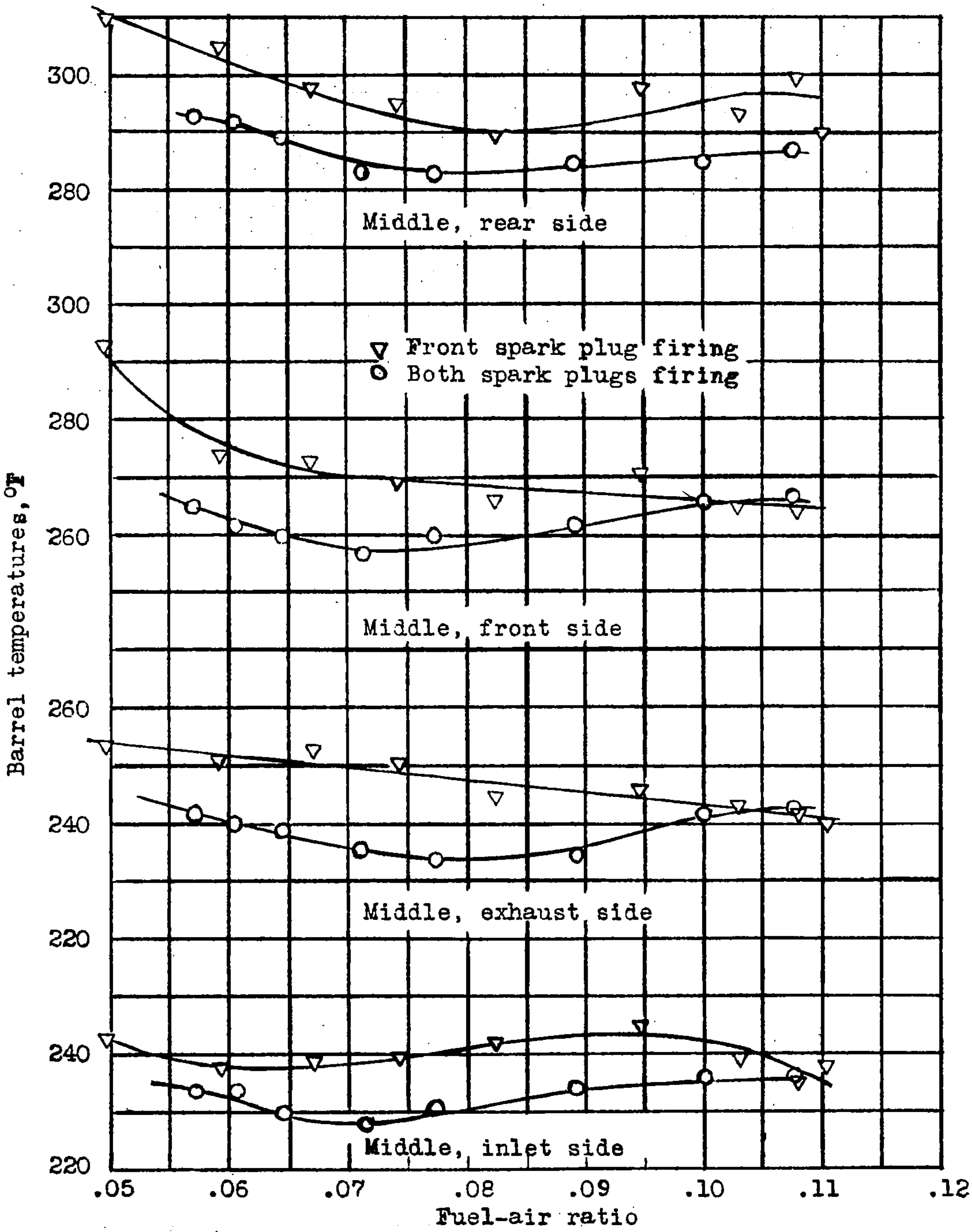

Figure 16.- Comparison of barrel temperatures with front spark plug firing and with both spark plugs firing. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of knock; inlet-air temperature, 150°F; temperature of rear spark-plug bushing, 400°F.

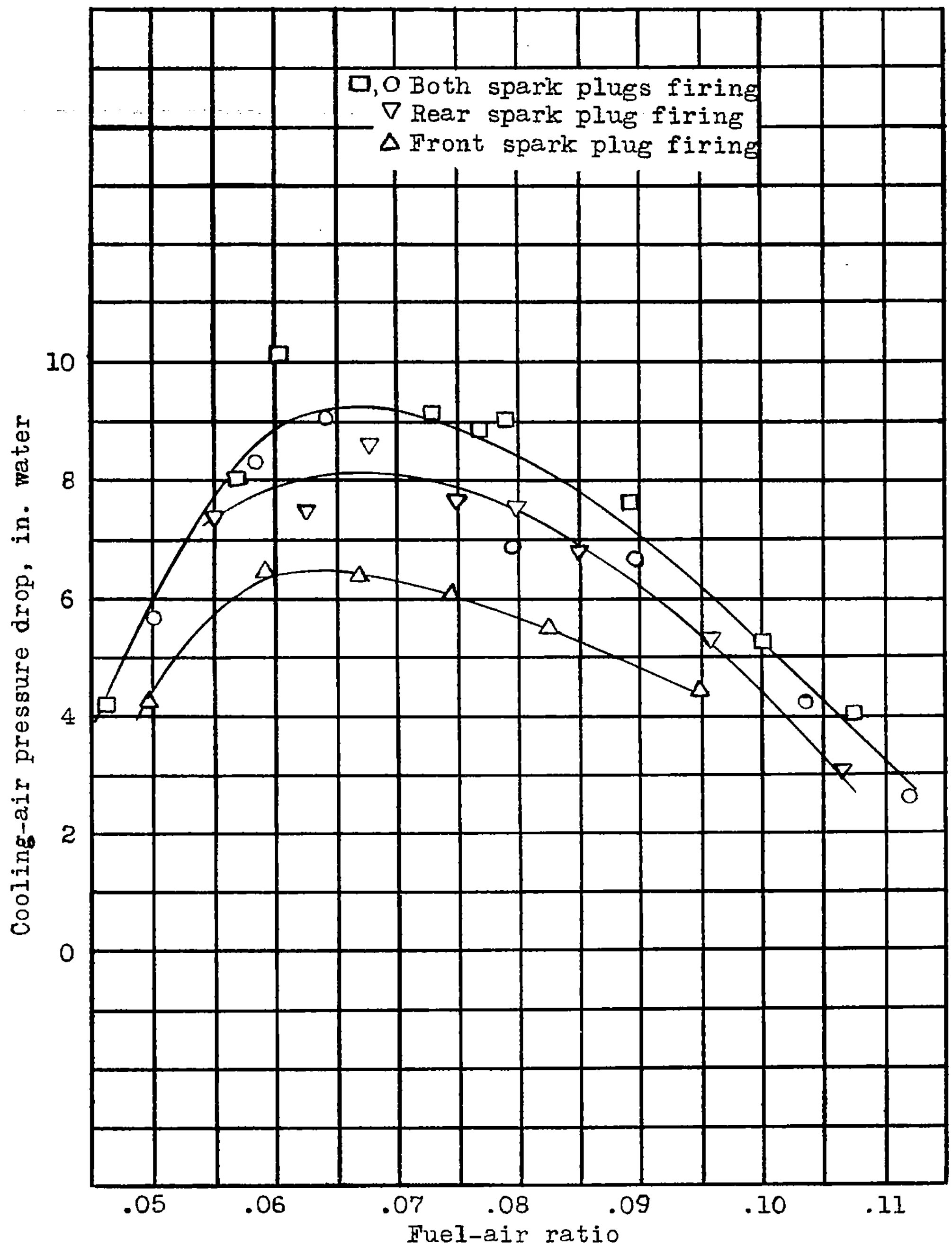

Figure 17.- Cooling-air pressure drop necessary to maintain rear spark-plug bushing at 400°F. Wright G-200 cylinder; engine speed, 2000 rpm; compression ratio, 7.0; fuel, S-1; spark advance, 20°; inlet pressure, 93 percent of knock; inlet-air temperature, 150°F; cooling-air temperature, 87°F to 92°F.